



Laval (Greater Montreal)

June 12 - 15, 2019

DEVELOPMENT OF ALKALI-ACTIVATED SCC: MICROSTRUCTURE AND PERFORMANCE UNDER SULFATE ATTACK

Dima M. Kanaan¹, and Ahmed M. Soliman²

^{1,2} Concordia University, Canada

¹ dima.kanaan@mail.concordia.ca

² ahmed.soliman@concordia.ca

Abstract: Alkali activated systems are getting popular in construction sector. This increases the demand to understand the performance of conventional and special types of concrete such as Self-consolidating concrete. An overview of the advances in alkali activated self-compacted concrete (AASCC) produced through activating aluminosilicate raw materials (i.e. precursors) is presented. A discussion for advantages of using different precursors and associated problems were also reviewed. Various attempts to produce AASCC based on fresh and hardened properties, durability performance and microstructure analysis were highlighted. There is a clear knowledge gap in durability performance of AASCC that requires research attention.

1 INTRODUCTION

Self-consolidating concrete (SCC) is considered one of the most advanced concrete technologies worldwide. However, it is no longer perceiving that attention due to its high content of cement leading to a high carbon footprint. Moreover, the reliance on cement manifested the concern associated with the disintegration problems of the long-standing structures; indicating the handicaps of Portland cement as a binder. Hence, reducing cement demand will preserve natural resources and reduce the amount of carbon dioxide (CO₂) emissions associated with cement production. Nowadays, the development of cement-less sustainable concrete is gaining a great attention due to its ecological value and environmental benefits.

On the other hand, Alkali-Activated Materials (AAMs) are considered part of the future toolkit towards sustainable binding systems. AAMs are produced by the utilization of low-carbon footprint materials (entitled “precursors”) activated in alkaline environments (induced by “activators”). In recent research, there has been an increasing emphasis on the utilization of these advanced cementing systems in the production of concrete for special purposes such as Self-Consolidating Concrete (SCC). Therefore, the main goal of Alkali-Activated Self-Consolidating Concrete (AASCC) is to produce eco-SCC that contains no cement without sacrificing its quality and performance. One of the main challenges facing AASCC application in the industrial-scale is the elaboration of effective mineral and chemical admixtures to improve the rheological, mechanical but most importantly durability performances.

The durability of AASCC is a subject of controversy, especially when exposed to sulfate attack. Furthermore, the adequacy of the classical sulfate immersion tests raises more concerns about the reported behavior. This was obvious from the research conducted by several investigators aiming for evaluating the dual aspects of AAMs potential and field-like quality. In the literature, AASCCs were not widely investigated as regular alkali-activated concretes (AACs). Effects of different parameters including (type and fineness of precursor(s), nature and dosage of alkali activator(s), chemical admixture(s), curing regime, mixing

procedure, nature and concentration of sulfates and exposure duration in deteriorating environments) on the fresh and hardened AASCC will be discussed based on the available literature highlighting knowledge gaps.

2 Fresh Properties

With the significant growth of SCC industry over the past 30 years, customer's demand accordingly has been changed. The traditional criterion of concrete performance from the perspective of concrete suppliers is subsumed under its transfer and arrival to the site only, yet this view should be expanded. The end result specification (ERS) refers to the "performance of concrete under in-situ testing", provides another potential criterion of testing (Bickley et al., 2006). From a practical standpoint, evaluating the in-situ SCC performance was based on direct assessment of its strength which represents the level of the industrial-wide understanding about SCC. On the other hand, testing for the rheology and fresh properties are marginalized. To develop a technically sound performance assessment, in-situ AASCC fresh tests should be experienced and addressed to certain criteria to meet the ERS. On the other hand, an expanded framework of validity old/new concepts and test methods should be monitored in construction sites.

2.1 Deformability and flow rate

Deformability is simply defined as "any change in dimension or shape" (ACI, 2013). It also refers to the ability of AASCC to flow into/and fill the formwork entirely under its own weight. Indeed, slump-flow (EN 12350-8) and T_{500} time tests can be used as primary indicators for flowability and flow rate of AASCC. Ushaa et al. (2015) studied the effect of using different precursors (i.e. FA, GGBFS, and silica fume (SF)) on the deformability of AASCCs. Mixtures were prepared using FA as the main precursor. The investigation concluded that replacing FA either with GGBFS at ratios (10%, 20%, and 30%) in addition to SF at (5%, 10%, and 15%) levels had resulted in satisfactory slump flow values ranging between 660-690 mm. Consequently, a lower dosage of superplasticizer was utilized. The T_{500} test results of AASCC mixtures were ranging between 4.5-6.5 s which were incompatible with EFNARC (2005) specifications. Generally incorporating SCMs, with the exception of SF, in concrete mixtures may increase the workability of fresh concretes depending on their type and dosage (Thomas, 2011; Lindgård et al., 2012). Fresh concrete mixtures containing SF are usually more cohesive and less prone to segregation than concrete mixtures without SF. As a result, increasing the content of SF would alter the mixtures to become more sticky (Yogendran et al., 1987; Khayat et al., 1997). With a varying effect of each precursor, higher percentages of GGBFS generally did not affect the flow rate of AASCCs as much as SF. This can be due to the high viscous nature of mixtures prepared with SF.

Lately, Shafiq et al. (2017) viewed the potential use of ceramic waste material in the production of AASCC. The authors added some broad perspective to the current debate on the use of alternative waste materials. The mixtures were prepared using a combination of Na_2SiO_3 and NaOH with two molarity levels i.e. 8M and 10M. Authors concluded that the utilization of two precursors (i.e. 50% slag and 50% ceramic waste) enhanced the deformability of the produced AASCC mixtures. In particular, workability was improved as low NaOH level (i.e. 8M) was used compared to high NaOH level (i.e. 12M). On the other hand, a reduction in the flowability was noticed as the slag content was increasing in the AASCC (Shafiq et al., 2017). This was ascribed to the low relative density of slag that caused an increase in the paste volume. Another study carried out by Patel et al. (2018) examined the effect of NaOH molarity and curing temperature on the workability and mechanical properties of AASCC. The investigation program consisted of two main phases. First, analyzing the performance of a reference AASCC mixture using FA as the main precursor. Second, reporting the fresh and hardened behavior of six AASCC mixtures produced by GGBFS. All mixtures were prepared using 14 mm crushed coarse aggregate, river sand as fine aggregate and Master Glenium Sky 8784 superplasticizer with relative density 1.10 to achieve the required flowability. Authors had attributed the reduction in mixtures' flowability to the use of slag along with increasing the NaOH molarity from 8M to 14M. As declared by authors, slag's irregular particle shape played a significant role in decreasing the fluidity relative to FA (Fig. 1). On the other hand, an increase in the viscosity and cohesiveness was observed as NaOH molarity was increasing from 8M to 14M. A similar conclusion was obtained by Sashidhar et al. (2015) in another study that adopted slag and FA in 50:50 proportions.

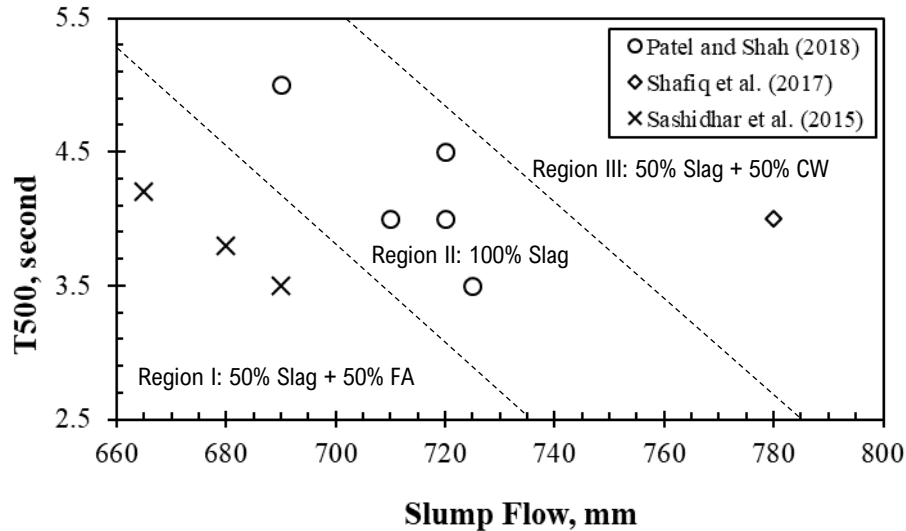


Figure 1: Relationship between T_{500} and slump flow tests [Adapted from Sashidhar et al. (2015); Shafiq et al. (2017); Patel et al. (2018)]

On the other hand, a very recent study by Muttashar et al. (2018) examined the feasibility of incorporating up to 100% of spent garnet as a replacement for river sand to achieve an enhanced AASCCs. Each mixture was produced using GGBFS as a sole precursor and a combination of alkaline NaOH and Na_2SiO_3 reagents. The solution molarity was kept constant at 8M and the ratio of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ was 2.5. It was concluded from the fresh behavior of the AASCCs (Table 1) that the satisfactory performance is ascribed to the shape, surface morphology and the particle size distribution of the spent garnet that enhanced the overall fresh state performance of AASCCs. Furthermore, the developed slump flow by 29mm during replacing sand by 100% spent garnet might be attributed to the effect of fineness modulus of spent garnet (i.e. 2.05) which is much less than the specified minimum value of sand (i.e. 2.3) according to ASTM C33 standard.

Table 1: Fresh properties of AASCCs with garnet replacing sand

Spent garnet%		Slump flow (mm)	T_{500} (s)	L-box ratio (H_2/H_1)
0%		671	5.5	0.91
25%		675	5.0	0.92
50%		681	4.5	0.93
75%		692	4.0	0.95
100%		700	3.5	0.97
EFNARC Guidelines	Minimum	650	2.0	0.80
	Maximum	800	5.0	1.00

2.2 Passing and stability abilities

Some of the criteria that are suggested by most of the investigators in a broader view were the passing ability and static stability of the produced AASCC mixtures as the utilization of water glass yielding to a viscous fluid. Passing ability refers to the capacity of an SCC mixture to flow through narrow spaces and restricted openings without blocking. The blocking mechanism assumes a flowable concrete (water-like) where at rest ($H_2/H_1 = 1.0$). Hence, the nearer this test value to 1.0, the more the blocking ratio to unity. Several test methods are used to measure the passing ability of SCC such as J-Ring (EN 12350-12), L-Box (EN 12350-10), and U-Box (EN 11044) tests. However, the potential of SCC to resist segregation and excessive bleeding is denoted as stability.

Memon et al. (2011) proved that adding water up to 20% may affect the flowability and stability of AASCC mixtures. In particular, increasing the water content by 10% had placed the mixture outside the EFNARC range in terms of J-Ring test, while extra added water by 15% and 20% had resulted in bleeding and segregation of mixtures. Ushaa et al. (2015) showed that passing ability more than 90% for AASCC can be achieved by replacing FA with slag and SF. Shafiq et al. (2017) highlighted the enhancement in the passing ability of AASCC mixtures prepared using precursor composed of 50% ceramic waste and 50% slag. On the other hand, Sashidhar et al. (2015) and Patel and Shah (2018) have shed light on the effect of increasing NaOH molarity $\geq 8M$ on the passing ability of AASCCs. Both studies linked the reduction in the passing ability and fluidity of mixtures with the increase in the activator viscosity. In particular, Patel and Shah (2018) noticed a reduction in the blocking ratio from 2% to 7% as the molarity increases from 8M to (10M, 12M, and 14M). Similarly, an increase in the J-Ring results by up to 75% was observed. This behavior was in line with the results obtained by Sashidhar et al. (2015) where 8 to 10% reduction in the passing ability was recorded as the molarity increased from 10M to 12M.

Manjunath and Narasimhan (2018) observed that increasing the slag binder content from 800 to 900 kg/m³ had increased the paste volume in mixtures leading to a higher passing ability. In addition, J-Ring test results for all mixtures were satisfying the EFNARC guidelines (<10 mm). Moreover, Muttashar et al. (2018) concluded that replacing natural sand by up to 100% spent garnet was found to enhance the passing ability of the produced mixtures (Fig. 2).

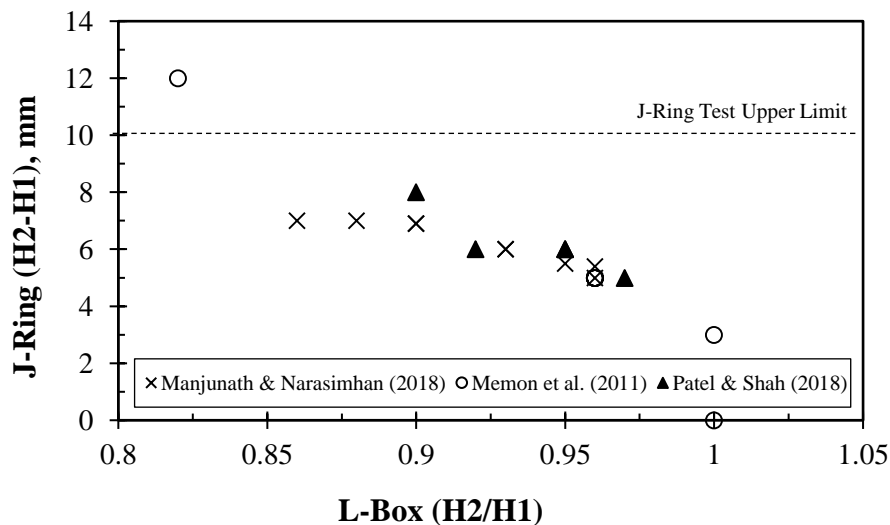


Figure 2: Relationship between J-Ring and L-Box tests [Adapted from Memon et al. (2011); Manjunath et al. (2018); Patel et al. (2018)]

3 Mechanical Properties


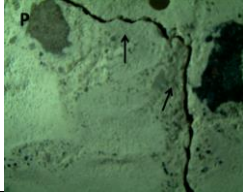
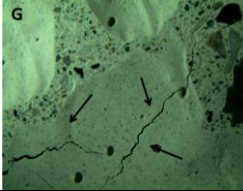
In order to move closer towards real practices, binding precursor materials and activators are classified according to their strength-giving characteristics. This evaluation technique can be applied at early (i.e. ≤ 7 days), late (i.e. ≥ 28 days) or even both ages. Various recent studies placed primary emphasis upon studying and characterizing AASCC at both ages (Memon et al., 2011; Nuruddin et al., 2011; Sashidhar et al., 2015; Ushaa et al., 2015; Kamseu et al., 2016; Manjunath and Narasimhan, 2018; Muttashar et al., 2018; Patel and Shah, 2018).

Experimental study carried by Sashidhar et al. (2015) to examine the potential of the locally available by-product materials (i.e. FA and GGBFS) in the production of AASCCs with adequate hardened properties. The produced mixtures had prepared by various activator molarity, namely 8M, 10M and 12M NaOH, FA and GGBFS with a content of 450 kg/m³ and water to binder ratio of 0.4. The study concluded that the AASCC mixture with 12M NaOH concentration level possessed the highest compressive strength value.

Also, the involvement of GGBFS has motivated mixtures to attain early age strength given that the curing process was under ambient temperature.

A recent research work was carried out by Kamseu et al. (2016) in order to explore the structural behaviour of metakaolin-based AASCCs activated by 8M NaOH and Na₂SiO₃/NaOH ratio of 3.0. The experimental investigation was carried out using three types of fine waste materials obtained from different waste management cycles (i.e. pumice (P), recycled glass (G) and feldspar sludge (F)). A total of ten mixtures were designed including a reference mixture (with 100% natural sand) and nine derived mixtures from the standard one. The mixtures were varying in the type of added fines i.e. P, G, and F in addition to the content added (i.e. 2.5%, 5%, and 7.5%). Results showed that using reactive fine materials is more efficient than using fillers. Reactive fines provide additional strengthening binding phases (with the remaining NaOH) into the pore solution. The formation of these extra bonds near the capillary pores will prevent the occurrence of intensive micro-cracks leading to strength development. According to authors, the variation in flexural strengths among the three fines was mainly due to the difference in the reactivity, packing behavior and amount of unreacted particles. For instance, the use of reactive pumice and recycled glass materials had enhanced the response of AASCCs to mechanical loading, however, feldspar revealed the optimum solution for pore refinement and fracture resistance. Furthermore, the improvement in the paste matrix, at the aggregate interface, granted the easy transfer of stresses. Similarly, Muttashar et al. (2018) discussed the influence of replacing sand by up to 100% spent garnet on the mechanical characteristics of AASCCs. Authors attributed the major reduction in the mechanical properties to the fineness and poor gradient of spent garnet particles leading to weak densification levels. Moreover, spent garnet replacement level of 25% of natural sand exhibited the optimum performance for both workability and mechanical characteristics. This can be due to the high contents of silica, alumina, and iron in the spent garnet (Table 2).

Table 2: Change in mechanical properties of various geopolymer composites [After Kamseu et al. (2016); Muttashar et al. (2018)]

Reference	Fines Types	Mix I.D.	Change in Strength, %		Micro-Cracks Propagation
			Compressive	Flexural	
Kamseu et al. (2016)	Feldspar	F1*	---	85.74	
		F2	---	126.17	
		F3	---	67.58	
Kamseu et al. (2016)	Pumice	P1*	---	8.40	
		P2	---	68.16	
		P3	---	60.94	
Kamseu et al. (2016)	Recycled Glass	G1*	---	30.47	
		G2	---	56.25	
		G3	---	48.83	
Muttashar et al. (2018)	Spent Garnet	TR1*	-2.04	-10.0	---
		TR2	-4.41	-20.0	---
		TR3	-5.50	-26.0	---
		TR4	-11.92	-34.67	---

*F (1-3): Sand Replacement by Feldspar (2.5-7.5%)

*P (1-3): Sand Replacement by Pumice (2.5-7.5%)

*G (1-3): Sand Replacement by Recycled Glass (2.5-7.5%)

*TR (1-4): Sand Replacement by Spent Garnet (25-100%)

Manjunath and Narasimhan (2018) presented the mechanical characteristics of AASCC mixtures produced using 100% slag. The very early age (i.e. 3-day) compressive and tensile strength results were ranging between 55 to 70 MPa and 2.25 to 3.7 MPa, respectively. This was attributed to the early formation of C-S-H gel in an alkaline environment. Similarly, the 28-day compressive and tensile strength tests reached approximately 80 and 3.9 MPa, respectively. This prominent high performance of AASCC mixtures was attributed to the full activation of slag yielding to a denser microstructure. At last, mixtures with the best engineering performance were chosen for the microstructural analysis. The outcomes emphasized the activation of slag grains through the development of a densified layer of C-S-H. According to the authors, increasing the content of the activated slag grains by alkaline solution had promoted the development of C-S-H and C-A-S-H gels in the matrix; which indeed led to strength elaboration. Although this may be true, the morphology of mixtures with the highest binder content (i.e. 900 kg/m³) showed a higher portion of C-S-H gel coupled with the lesser content of activated slag. In other words, the alkaline solution activator quantity was insufficient to activate that higher content of slag grains.

4 Durability Performance: Sulfate Attack

Sulfate attack is commonly avowed as one of the most antagonistic environments to concrete structures. It generates severe deteriorations leading to a shorter service life (Najimi et al., 2011). It is frequently defined as “synthesis of complex and overlapping chemical operations and physical activities caused by deteriorative reactions between paste components and sulfate ions from external or internal sources” (Marchand et al., 2003; Najimi et al., 2011). In fact, physical sulfate attack repercussions are distinctive from those of chemical sulfate attack since it eventuates to surface degradation. However, expansion and cracks are the consequences of the chemical sulfate attack owing to the formation of ettringite and gypsum (Mehta, 2000). Hence, utilization of the generic terminology “sulfate attack” in the in-situ domain towards depicting concrete deterioration caused by sulfate ions may generate perplexity and confusion between physical and chemical attack processes (Haynes et al., 1996; Suleiman, 2014). The adverse effect of sulfate on concrete structures depends on several parameters such as the quality of concrete, nature, and concentration of sulfate...etc. Alkalinity in the cement pores is another key factor where any medium with low pH value (i.e. <12.5) represents an aggressive atmosphere for cement matrix.

Eventually, utilization of AAMs as an alternative to OPC systems may exhibit high resistance to sulfate attack. This might be due to the polycondensation of the main elemental reaction products in a 3-D network structure during the activation of aluminosilicate precursor(s) under alkaline atmosphere. Generally, C-A-S-H and C-S-H gels are believed to have a similar tobermorite structure (Sun et al., 2006; Provis and Bernal, 2014). Whereas the chemical composition and structure of Na and/or K attached to Si-O-Al bonds are similar to zeolites structure (Lecomte et al., 2003).

To the best of authors’ knowledge, most of the sulfate attack research were conducted on conventional alkali activated concrete or small mortar specimens to explore the behaviour. Hence, the following paragraphs highlights these most recent findings that support the potential for achieving AASCC.

The concern related to the resistance of low-calcium AACs to sulfate solutions was deliberated by several researchers (T. Bakharev, 2005; Thokchom et al., 2010). The behaviour of alkali-activated FA (class-F) concretes prone to 5% Na₂SO₄, 5% MgSO₄ and 5% Na₂SO₄ + 5% MgSO₄ for 5 months was examined by T. Bakharev (2005). In the Na₂SO₄ solution, the compressive strengths of alkali-activated mixtures by NaOH + KOH and Na₂SiO₃ activators decreased by 65% and 18%, respectively. Furthermore, an increase in the strength by 4% was noted while the utilization of NaOH only. Quite the reverse, in MgSO₄ solution an increase in the strength was observed during the utilization of NaOH and NaOH + KOH activators by 12% and 35%, respectively, while a reduction by 24% was observed in Na₂SiO₃ activated mixture. This was attributed to the migration of alkalis into solution while the exposure to Na₂SO₄. In MgSO₄ solutions, both mixtures prepared using Na₂SiO₃ and a mixture of NaOH + KOH showed the migration of alkalis into sulfate solutions and diffusion of Mg²⁺ and Ca²⁺ to the subsurface areas of specimens. It was noted that the exposure to a combination of 5% Na₂SO₄ + 5% MgSO₄ resulted in the least strength changes. The best performance was observed for mixtures activated by NaOH owing to its stable cross-linked aluminosilicate polymer structure. At last, the immersion in more concentrated solutions i.e. 5% Na₂SO₄ + 5% MgSO₄ created fewer changes in the strength of the alkali-activated specimens than immersion in less concentrated

ones. A contradictory observation was found in OPC specimens where the most significant deterioration was found in concentrated solution.

Research work carried by Thokchom et al. (2010) reported the performance of alkali-activated FA (class F) mortars while the exposure to 10% MgSO_4 solution for 24 weeks. The mortar specimens were cured thermally in an oven for 48-hour under 85°C . The variation in Na_2O % was found to have a significant influence on the pH value. The visual inspection results showed white anhydrite deposits (CaSO_4) on the specimen's surfaces during exposure to a MgSO_4 solution which gradually transformed from soft to hard shape with an additional gain in weight. Generally, mortars produced with higher Na_2O % behaved better than those with lower alkali content with a maximum strength of 89.7%. This can be attributed to the increase in the pH of mixtures due to the migration of more alkalis from specimens into the MgSO_4 solution.

The most extensive study on the effect of external sulfate attack on the mechanical and microstructural properties of alkali-activated slag (AAS) was made by Komljenović et al. (2013). The investigation program consisted of two main phases. First, analysing the properties of the Portland-slag cement (CEM II/ A-S 42.5N) as the benchmark material of the produced mortars. Second, reporting the performance of the AAS during the 5% Na_2SO_4 exposure. The total water to solid ratio including the sodium silicate activator was 0.28. After 28 days of curing in a humid chamber at ambient temperature condition, mortar prisms were exposed to 5% Na_2SO_4 for up to 90 days. It was observed from that the exposure had led to a decrease in strength of CEM II, but not of AAS samples. The compressive strength of both CEM II and AAS groups after 30 days in the sulfate-rich environment was slightly increased by 1.05 and 1.07, respectively. After 60 days of sulfate attack, AAS relative strength remained on the same level i.e. 1.07 while in CEM II it started to decrease i.e. 0.97. At the end of the exposure period, CEM II relative strength continued to decrease i.e. 0.90, whereas AAS relative strength slightly increased i.e. 1.11. Strength loss of 9% in the case of CEM II was ascribed to the microstructural changes. In addition, the expansion of the matrix in the aggressive sulfate environment due to the transformation of monosulfate crystals embedded in the C-S-H to ettringite and gypsum. On the other hand, mortars prepared using AAS showed no strength loss compared to Portland-slag cement mortars. A strength gain of 11% was observed in the AAS mortar as a result of the high alkalinity of the sulfate medium through the continuous formation of AAS reaction products. Lastly, calcite was detected in both mortars after 28-day of curing in a humid chamber as a result of the carbonation process.

An experimental study related to the influence of 5% Na_2SO_4 and 5% MgSO_4 solutions on alkali-activated slag – ultrafine palm oil fuel ash (POFA) mortars was conducted by Yusuf (2015). The experimental work was carried by testing three alkali-activated mortars with/without slag by varying the ($\text{Na}_2\text{SiO}_3/\text{NaOH}$) ratio between 2.5 and 1.0. Generally, the inclusion of slag up to 20% in mortars has contributed to better sulfate resistance. On the other hand, the variation in the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio has resulted in negligible strength retention difference. After 6-months of continuous immersion in Na_2SO_4 and MgSO_4 solutions, the residual strengths recorded for the slag free mortars were 16.5% and 76.8%, respectively. The investigation attributed the severe deterioration of mortars exposed to 5% Na_2SO_4 solution to the leaching of active minerals (Ca^{2+} , Mg^{2+} , Na^+) instigating the disintegration of microstructural framework (Fig. 3). On the other hand, better strength retention was observed in MgSO_4 solution owing to the formation of surficial white deposits and crystallized anhydrite (CaSO_4) as presented in (Fig. 4). The results obtained from this study showed a very good agreement with previous experimental results conducted by Salami et al. (2017) in terms of the resistance to sulfate attack. The exposure to 5% Na_2SO_4 and 5% MgSO_4 solutions for 9 months confirmed that the deterioration of mortars depends on the type of cations carried by sulfate solutions.

On the other hand, Mithun and Narasimhan (2016) study the potential of producing sulfate resistance alkali-activated slag concrete using copper slag (CS) as an alternative to natural river sand. The study indicated the use of OPC-based control mixture, as a basis, for the design of five alkali-activated slag-based mixtures with CS up to 100% by volume. The alkali solution used was a mixture of liquid Na_2SiO_3 and NaOH with $\text{SiO}_2/\text{Na}_2\text{O}$ ratio of 1.25. The investigation concluded that the replacement of CS by natural sand has reinforced the produced OPC and alkali-activated mixtures. After 12 months of exposure to 10% Na_2SO_4 solutions, no strength deterioration was observed in conventional and alkali-activated mixtures with CS. While, in 10% MgSO_4 solutions, both groups of mixtures suffered from a higher rate of degradation; alkali-activated mixtures being the most. This can be attributed to the absence of calcium hydroxide $\text{Ca}(\text{OH})_2$

after its reaction with $MgSO_4$ solutions leading to the nonstop attack of Mg ions to C-S-H structure. The result was the formation of expansive products i.e. M-S-H and gypsum, henceforth, AAC cracking.

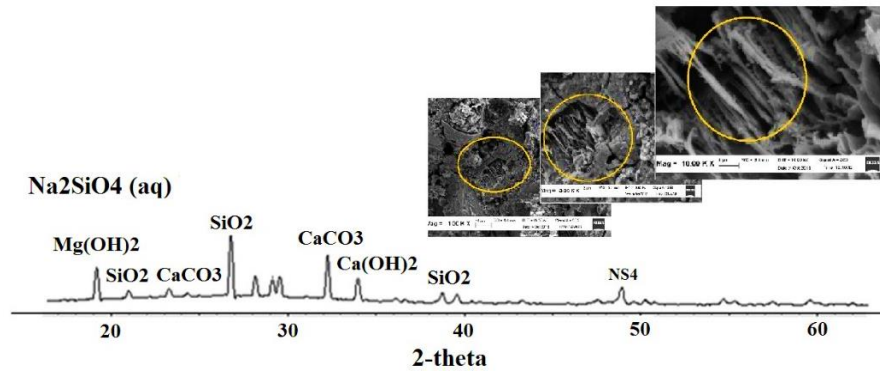


Figure 3: SEM micrographs and XRD patterns of mortars with 20% slag exposed to Na_2SiO_4 [Adapted from Yusuf (2015)]

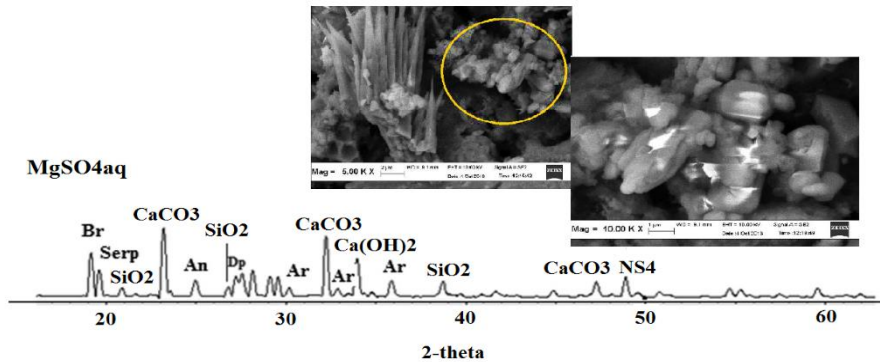


Figure 4: SEM micrographs and XRD patterns of mortars with 20% slag exposed to $MgSO_4$ where An: Anhydrite ($CaSO_4$), Ar: Aragonite ($CaCO_3$), DP: Diopside ($MgCaSi_2O_6$) [Adapted from Yusuf (2015)]

5 CONCLUSIONS

In recent years, there has been an increasing emphasis on the durability of concrete under sulfate attack environments as well as increasing concern about their premature failure and costly rehabilitation techniques (Skalny and Thaulow, 2002). Current knowledge indicates clearly a gap between the laboratory research results and the actual field conditions. These conflicting forces have helped create a burgeoning interest in alternative forms of mitigating assessments. The current assessment policies and practices coupled with the conventional classical sulfate immersion tests are in a period of rapid transformation due to the variability between the controlled laboratories and actual field conditions.

Indeed, direct assessment tests which frequently referred to as "single damaging factor techniques" have raised the doubt on their reliability and efficiency in motivating the efforts to question assessments. Deteriorated concrete structures are often due to an array of mechanisms (chemical, physical and microstructural) acting in a synergistic manner. The lack of consistent standardized durability tests procedures has guided the world to a universal shift to performance-based assessment. It is argued that the development of performance-based tests that include multi-damaging mechanisms are necessary for better modeling of the performance of concrete structures (Beushausen and Fernandez-Luco, 2015). Such authentic techniques derive their value primarily from being effective in assessing special types of concretes such as AASCC, which apparently encompasses high contents of waste-based precursor materials.

To summarise, all durability specifications and related standards were established assuming OPC as the key binder. The inadequacy of the current standards in considering the replacement of OPC by AAMs has limited its expansion in the market. Few attempts to study the resistance of AAC to sulfate attack were recorded. On the other hand, there is still a dearth of information on the resistance of AASCC prone to these environments.

6 REFERENCES

- ACI. (2013). ACI concrete terminology. *ACI CT-13*.
- Bakharev, Sanjayan, J., and Cheng, Y.-B. (2002). Sulfate attack on alkali-activated slag concrete. *Cement and Concrete Research*, **32**(2), 211-216.
- Bakharev, T. (2005). Durability of geopolymer materials in sodium and magnesium sulfate solutions. *Cement and Concrete Research*, **35**(6), 1233-1246.
- Beushausen, H., and Fernandez-Luco, L. (2015). Performance-based specifications and control of concrete durability. *State-of-the-Art Report RILEM TC 230-PSC*.
- Bickley, J., Hooton, R. D., and Hover, K. C. (2006). Preparation of a performance-based specification for cast-in-place concrete. *RMC Research Foundation*, 1-36.
- EFNARC. (2005). The European guidelines for self-compacting concrete specification, production and use. *Self-compacting concrete*.
- Haynes, H., O'Neill, R., and Mehta, P. K. (1996). Concrete Deterioration From Physical Attack By Salts. *Concrete International*, **18**(1), 63-68.
- Kamseu, E., Ponzoni, C., Tippayasam, C., Taurino, R., Chaysuwan, D., Sglavo, V. M., Thavorniti, P., and Leonelli, C. J. J. o. B. E. (2016). Self-compacting geopolymer concretes: Effects of addition of aluminosilicate-rich fines. *5*, 211-221.
- Khayat, K. H., Vachon, M., and Lanctot, M.-C. J. M. J. (1997). Use of blended silica fume cement in commercial concrete mixtures. **94**(3), 183-192.
- Komljenović, M., Bašćarević, Z., Marjanović, N., and Nikolić, V. (2013). External sulfate attack on alkali-activated slag. *Construction and Building Materials*, **49**, 31-39.
- Lecomte, I., Liégeois, M., Rulmont, A., Cloots, R., and Maseri, F. J. J. o. m. r. (2003). Synthesis and characterization of new inorganic polymeric composites based on kaolin or white clay and on ground-granulated blast furnace slag. **18**(11), 2571-2579.
- Lindgård, J., Andiç-Çakır, Ö., Fernandes, I., Rønning, T. F., and Thomas, M. D. (2012). Alkali-silica reactions (ASR): literature review on parameters influencing laboratory performance testing. *Cement and Concrete Research*, **42**(2), 223-243.
- Manjunath, R., and Narasimhan, M. C. (2018). An experimental investigation on self-compacting alkali activated slag concrete mixes. *Journal of Building Engineering*, **17**, 1-12.
- Marchand, J., Odler, I., and Skalny, J. P. (2003). *Sulfate attack on concrete*: CRC Press.
- Mehta, P. K. (2000). Sulfate attack on concrete separating myths from reality. *Concrete International*, **22**(8), 57-61.
- Memon, F., Nuruddin, F., and Shafiq, N. (2011). Compressive strength and workability characteristics of low-calcium fly ash-based self-compacting geopolymer concrete. *International journal of civil and environmental engineering*, **3**(2), 72-78.
- Mithun, B. M., and Narasimhan, M. C. (2016). Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate. *Journal of Cleaner Production*, **112**, 837-844.
- Muttashar, H. L., Ariffin, M. A. M., Hussein, M. N., Hussin, M. W., and Ishaq, S. B. J. J. o. B. E. (2018). Self-compacting geopolymer concrete with spend garnet as sand replacement. **15**, 85-94.
- Najimi, M., Sobhani, J., and Pourkhorshidi, A. (2011). Durability of copper slag contained concrete exposed to sulfate attack. *Construction and Building Materials*, **25**(4), 1895-1905.
- Nuruddin, M. F., Demie, S., and Shafiq, N. (2011). Effect of mix composition on workability and compressive strength of self-compacting geopolymer concrete. *Canadian Journal of Civil Engineering*, **38**(11), 1196-1203.

- Patel, Y. J., and Shah, N. (2018). Study on Workability and Hardened Properties of Self Compacted GEOPOLYMER Concrete Cured at Ambient Temperature. *Indian Journal of Science and Technology*, **11**(1).
- Provis, J., and Bernal, S. (2014). *Geopolymers and Related Alkali-Activated Materials* (Vol. 44).
- Sashidhar, C., Jawahar, J. G., Neelima, C., and Kumar, D. P. (2015). Fresh and Strength Properties of Self compacting Geopolymer Concrete Using Manufactured Sand. *International journal of ChemTech Research (IJCRGG)*, **8**, 183-190.
- Shafiq, I., Azreen, M., and Hussin, M. (2017). *Sulphuric Acid Resistant of Self Compacted Geopolymer Concrete Containing Slag and Ceramic Waste*. Paper presented at the MATEC Web of Conferences.
- Skalny, J., and Thaulow, N. (2002). *Sulfate attack in North America*. Paper presented at the Proceedings of the 1st international conference on thaumasite in cementitious materials, Garston, UK.
- Suleiman, A. R. (2014). Physical sulphate attack on concrete.
- Sun, G., Young, J. F., and Kirkpatrick, R. J. (2006). The role of Al in C–S–H: NMR, XRD, and compositional results for precipitated samples. *Cement and Concrete Research*, **36**(1), 18-29.
- Thokchom, S., Ghosh, P., and Ghosh, S. (2010). Performance of fly ash based geopolymer mortars in sulphate solution. *Journal of engineering science and technology review*, **3**(1), 36-40.
- Thomas, M. (2011). The effect of supplementary cementing materials on alkali-silica reaction: A review. *Cement and Concrete Research*, **41**(12), 1224-1231.
- Ushaa, T., Anuradha, R., and Venkatasubramani, G. (2015). Performance of self-compacting geopolymer concrete containing different mineral admixtures.
- Yogendran, V., Langan, B., Haque, M., and Ward, M. J. M. J. (1987). Silica fume in high-strength concrete. **84**(2), 124-129.